Part D: Specifying concrete for general cast-in-situ use

D1. Introduction

This Part provides guidance on concrete quality and any Additional Protective Measures (APM) required to provide resistance to chemical attack. It caters primarily for the general use of cast-in-situ concrete, but additionally will cover any precast concrete that does not meet the qualifying ‘carbonation’ conditions that apply to precast concrete in Parts E and F.

The starting point is the ACEC Class of the ground, derived in Part C, plus some knowledge of the type, use and geometry of the concrete element and the ground conditions to which it will be subject.

Some important changes have been made to the previously published guidance. These are explained in Section D2. The overall Design process is summarised in Section D3. Sections D4 to D8 give the detailed guidance. A glossary of terms is to be found in Appendix A1 of Part A.

D2. Changes since SD1: 2003

Some important changes to the way concrete quality is specified are made in this Special Digest. These stem from a further study of occurrences of sulfate attack in concrete structures and recent field and laboratory research (see Section A3). The key changes are as follows:

(i) The concrete quality recommended now takes account of the possibility of an external source of carbonate. Recent research has shown that there is often sufficient bicarbonate, \((\text{HCO}_3)^-\), in the groundwater to result in TSA when sulfate levels are high and the temperature cool.

(ii) The concept of Aggregate Carbonate Range is no longer included. Since the concrete quality takes account of a possible external source of carbonate, it also inherently caters for an internal source from carbonate in aggregates and ACR is redundant.

(iii) Starred (Range B aggregates) and double-starred (Range C aggregates) are no longer valid and not included. The concept for these was dependant on the now redundant Aggregate Carbonate Range.

(iv) Changes have been made in the recommended maximum w/c ratio and minimum cement/combination content. These stem from the new research on the quality of concrete necessary to resist sulfate attack, including TSA.

(v) Changes have been made in the presentation of classification of cements/combinations. However, the basic ranking with respect to performance in sulfate-bearing ground is mostly unchanged,

(vi) The number of APM to be applied at higher sulfate levels has been reduced, in general by two. This follows from a higher level of confidence in the provisions for the concrete.

(vii) The use of the concept ‘Intended Working Life’ replaces that of ‘Structural Performance Level’. This is for harmony with European standards such as BS EN 206-1.

(viii) Section width is no longer taken as a principal factor when finding a DC Class to cater for assessed ACEC conditions. Instead, footnotes call for adjustments to be made for section widths of less than 140 mm and greater than 450 mm in particular circumstances.

(ix) No relaxation is made in respect of ‘carbonation’ in the general use of cast-in-situ concrete. Such benefits were difficult to ensure in practical conditions.

D3. The design process

The overall process of design of concrete for use in aggressive ground conditions is summarised in Figure A1 of Part A. Part D deals with Stages 3 and 4 of the overall process. Further detail is given diagrammatically in Figure D1.

For each ACEC Class determined in Part C, concrete quality is specified (in Table D1) in terms of a Design Chemical Class (DC Class), taking account of Intended Working Life (IWL), section thickness and the hydrostatic pressure to which it may be subjected.

Each DC Class is prescribed in Table D2 and follows the previous practice of defining concrete quality for each cement or combination group respectively in terms of:

- maximum free water/cement ratio, or free water/comination ratio;
- minimum cement content, or combination content.
Firstly, from a consideration of the intended structure, determine parameters:
- ACEC Class of ground from Table C1;
- Intended Working Life of concrete element (see categories in Table D1);
- Thickness of concrete element (see categories in Notes b & c, Table D1);
- Hydrostatic conditions for concrete element (see Note a, Table D1).

From Table D1, determine the appropriate DC Class of concrete:
- For the assessed ACEC Class, look in the column corresponding to the required Intended Working Life, taking account of Notes d & e;
- Adjust DC Class or Number of APM up or down to take account of (i) thickness of concrete section - see Notes b & c; (ii) hydrostatic pressure if this exceeds 5 x section thickness - see Note a.

From Table D1, find requirements for Additional Protective Measures (APM):
- determine the number required;
- note any restrictions as to choice, eg instruction to use APM3;

From Table D4, guided by Section D6, select appropriate options for APM, taking account of any restrictions and engineering practicalities.

Include in the Contract documents:
- Design Sulfate (DS) Class of ground;
- ACEC Class of ground;
- Hydrostatic conditions;
- Specified DC Class after optional adjustment/enhancement;
- Specified number of APM after adjustment;
- Any restrictions/preferences in respect of APM to be used;
- Any other design requirements for each concrete element.

Obtain from the Contract Documents:
- the specified DC Class;
- the number and type of APM;
- any other design requirements for each concrete element.

Formulate the concrete mix design for the element, using Table D1 to achieve the specified DC Class. Other factors will include strength class of concrete, the consistence, the availability and cost of materials and any other contract requirements.

Figure D1: Specification of concrete for general cast-in-situ use
In some cases, Additional Protective Measures (APM) are recommended in Table D1 to further protect the concrete. The number of APM needed increases both with higher ACEC Class of the ground and with higher Intended Working Life required for the concrete element. The various APM options are listed in Table D4 and APM are discussed in Section D6.

D4. Selection of the DC-class and APM
D4.1 Background
The DC (Design Chemical) classification was introduced in Digest SD1:2001 as a new way of defining ‘qualities’ of concrete that are required to resist chemical attack. Section D4 deals with the derivation, in Table D1, of the DC Class from the ACEC Class of the ground (from Table C1), taking into account a number of factors, including the type of concrete element, its mode of exposure to the aggressive ground, and the required durability. The options for limiting values of concrete required to satisfy the various DC Classes are discussed in Section D5.

D4.2 Key factors
The key factors in using Table D1 are as follows:
(i) Recommendations for concrete specification in terms of DC Class for each of the ACEC Classes are given for two categories of Intended Working Life in Table D1. There is an obvious parity in the correlations except at the AC-5 level, where the DC-4 family are recommended, as no DC-5 Classes are defined. To compensate for this it is recommended that, wherever practical, APM3 (provide surface protection) should be applied to the concrete.
(ii) APM are also recommended in Table D1 for some other cases, where a working life of ‘at least 100 years’ is required for concrete subjected to high sulfate allied to Mobile groundwater conditions (ie where the AC Class does not have an ‘s’ suffix that indicates Static groundwater). Here, any APM option of the five listed in Table D4 may be chosen providing the application advice given in Section 6 is followed.
(iii) The given ACEC / DC Class / APM correlations in Table D1 apply where the differential water pressure across the concrete element (hydrostatic head) is not more than five times the section width. The hydrostatic head will normally need to be estimated from a consideration of the likely water levels on either side of the element. Applications of concrete that may give rise to differentials include ground-retaining structures, and basement walls and tanks within the ground.
(iv) When the hydrostatic head is more than five times the section thickness a more cautious design is required (see Note ‘a’ of Table D1). Either the DC Class should be increased by one ‘step’, or an additional APM should be employed. An exception may be made where APM3 (provide surface protection) has already been selected for application, either as a mandatory measure for AC-5 level conditions, or as a first ‘APM of choice’
(v) Adjustments to the given ACEC / DC Class / APM correlations are also applicable when the section thickness is 140 mm or less, or when it is greater than 450 mm.
• 140 mm or less - a more cautious design is required. The recommended approach is similar to that for high hydrostatic head (see Note ‘b’ of Table D1).
• greater than 450 mm - a relaxation of one step in DC Class may be applied provided that, for reinforced concrete, APM4 (provide sacrificial layer) is applied – see Section D6.5. Since such a relaxation implies some degree of chemical attack is acceptable it will not be appropriate where concrete surfaces must retain their integrity to provide frictional resistance against the ground, as in friction piles and the bases of ‘L’ section retaining walls.
(vi) The DC classes carry the suffix ‘m’ or ‘z’ where these were part of the corresponding ACEC class designations. Suffix notations ‘z’ indicate concretes that primarily must resist acid conditions and ‘m’ indicate concretes that must resist high levels of magnesium sulfate. Note is taken of these when specifying concrete composition – see Section D5.
Table D1: Selection of the DC Class and the number of APM where the hydrostatic head is not more than five times the section thickness $^{a,b,c}$

<table>
<thead>
<tr>
<th>ACEC Class</th>
<th>Intended Working Life</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At least 50 years $^{d,e}$</td>
<td>At least 100 years</td>
</tr>
<tr>
<td>AC-1s, AC-1</td>
<td>DC-1</td>
<td>DC-1</td>
</tr>
<tr>
<td>AC-2s, AC-2</td>
<td>DC-2</td>
<td>DC-2</td>
</tr>
<tr>
<td>AC-2z</td>
<td>DC-2z</td>
<td>DC-2z</td>
</tr>
<tr>
<td>AC-3s</td>
<td>DC-3</td>
<td>DC-3</td>
</tr>
<tr>
<td>AC-3z</td>
<td>DC-3z</td>
<td>DC-3z</td>
</tr>
<tr>
<td>AC-3</td>
<td>DC-3</td>
<td>DC-3 + one APM of choice</td>
</tr>
<tr>
<td>AC-4s</td>
<td>DC-4</td>
<td>DC-4</td>
</tr>
<tr>
<td>AC-4z</td>
<td>DC-4z</td>
<td>DC-4z</td>
</tr>
<tr>
<td>AC-4</td>
<td>DC-4</td>
<td>DC-4 + one APM of choice</td>
</tr>
<tr>
<td>AC-4ms</td>
<td>DC-4m</td>
<td>DC-4m</td>
</tr>
<tr>
<td>AC-4m</td>
<td>DC-4m</td>
<td>DC-4m + one APM of choice</td>
</tr>
<tr>
<td>AC-5z</td>
<td>DC-4z + APM3 $^{f}$</td>
<td>DC-4z + APM3 $^{f}$</td>
</tr>
<tr>
<td>AC-5</td>
<td>DC-4 + APM3 $^{f}$</td>
<td>DC-4 + APM3 $^{f}$</td>
</tr>
<tr>
<td>AC-5m</td>
<td>DC-4m + APM3 $^{f}$</td>
<td>DC-4m + APM3 $^{f}$</td>
</tr>
</tbody>
</table>

Notes

a Where the hydrostatic head of groundwater is greater than five times the section thickness, one step in DC Class or one APM over and above the number indicated in the table should be applied except where the original provisions included APM3. Where APM3 is already required, an additional APM is not necessary.

b A section thickness of 140 mm or less should be avoided in in-situ construction but where this is not practical, apply one step higher DC Class or an additional APM except where the original provisions included APM3. Where APM3 is already required, an additional APM is not necessary.

c Where a section thickness greater than 450 mm is used and some surface chemical attack is acceptable, a relaxation of one step in DC Class may be applied, provided that for reinforced concrete APM4 (sacrificial layer) is applied – see Section D6.5.

d The concrete quality given in column ‘at least 50 years’ is also adequate for foundations to low-rise domestic housing with an intended working life of ‘at least 100 years’.

e Structures with an intended working life of ‘at least 50 years’ but with a high consequence if they were to fail should be classed as having an intended working life of ‘at least 100 years’ for the selection of the DC Class.

f Where APM3 is not practical, see Section D6.1 for guidance.
D5. Composition of concrete to resist chemical attack

D5.1 Background
The main factors that determine the resistance of concrete to aggressive ground are its water / cement \( (w/c) \) ratio and the cement / combination type used. In the previous Special Digest, the importance of carbonate in the aggregates was stressed in relation to TSA. A source of carbonate is still considered essential for occurrence of TSA, but recent research has shown that sufficient carbonate can come from bicarbonate in groundwater. As a consequence, the limiting values of concrete composition are based on the assumption that the concrete is made with high carbonate aggregates (the worst case).

Recent research has also shown that resistance to sulfate attack is not a function of cement content. Concretes made with the same materials, the same w/c ratio but different cement / combination contents have similar sulfate resistance providing there is sufficient fine material to give a closed structure. As there is not yet any agreed method for verifying that the concrete has a closed structure, this Special Digest continues to recommend a minimum cement / combination content.

A compressive strength requirement has never formed part of BRE Digest recommendations for sulfate resistance. However, it is recognised that the specification may need to contain a compressive strength class requirement for structural purposes and / or the protection of reinforcement against corrosion due to carbonation or chlorides.

Much of the recent research (see Section A3) has been focussed on determining what is an adequate concrete specification and the performance of different cement types. The findings of this research are incorporated into the recommendations given in Table D2. It is not possible to generalise and say they are the same, less stringent or more stringent than the previous Special Digest. What were the requirements for concrete made with aggregate carbonate ranges B and C (medium and low carbonate) have been increased to those given previously for concrete made with range A aggregates (high carbonate). However, the excellent performance of concrete made with sulfate resisting slag cements has been recognised and there is some relaxation of the requirements with these cements. On the other hand the mixed performance of concrete made with SRPC in sulfate conditions conducive to TSA has led to some tightening of the requirements. The performance of pulverized fly ash (pfa) cements and combinations is still under investigation and so a conservative approach to their use is taken.

The effectiveness of these concretes to resist chemical attack depends to a high degree on their impermeability. Therefore, good compaction is most important. With low w/c ratios, such as those advocated here, it is probable that water-reducing admixtures will be necessary to achieve effective compaction. This is particularly true of concretes such as those used in piling where mechanical compaction cannot be used.

The recommended concrete qualities are given in Table D2.

D5.2 Use of Table D2
For a given DC Class, specifications for concrete are given in Table D2 in terms of maximum free water / cement or combination ratio and minimum cement or combination content for standard aggregate sizes, and recommended types of cement or combination. The cements and combinations are in new Groups, designated A through to G, that are defined in Table D3 (see Section D5.3).

Table D2 provides a wide range of options for concrete at any DC Class level so that, in most cases, the concrete producer can use a cement or combination from normal stock.
### Table D2: Concrete qualities to resist chemical attack for the general use of in-situ concrete

<table>
<thead>
<tr>
<th>DC-class</th>
<th>Maximum free water / cement or combination ratio</th>
<th>Minimum cement or combination content (kg/m³) for maximum aggregate size of:</th>
<th>Recommended cement and combination group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>≥ 40 mm</td>
<td>20mm</td>
</tr>
<tr>
<td>DC-1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DC-2</td>
<td>0.55</td>
<td>300</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>320</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>360</td>
<td>380</td>
</tr>
<tr>
<td>DC-2z</td>
<td>0.55</td>
<td>300</td>
<td>320</td>
</tr>
<tr>
<td>DC-3</td>
<td>0.50</td>
<td>320</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>360</td>
<td>380</td>
</tr>
<tr>
<td>DC-3z</td>
<td>0.50</td>
<td>320</td>
<td>340</td>
</tr>
<tr>
<td>DC-4</td>
<td>0.45</td>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>360</td>
<td>380</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>DC-4z</td>
<td>0.45</td>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td>DC-4m</td>
<td>0.45</td>
<td>340</td>
<td>360</td>
</tr>
</tbody>
</table>

### Grouped cements and combinations

<table>
<thead>
<tr>
<th>Cements</th>
<th>Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CEM I, CEM II/A-D, CEM II/A-Q, CEM II/A-S, CEM II/B-S, CEM II/A-V, CEM II/B-V, CEM III/A, CEM III/B</td>
</tr>
<tr>
<td>B</td>
<td>CEM II/A-L⁺, CEM II/A-LL⁺</td>
</tr>
<tr>
<td>C</td>
<td>CEM II/A-L⁺, CEM II/A-LL⁺</td>
</tr>
<tr>
<td>D</td>
<td>CEM II/B-V+SR, CEM III/A+SR</td>
</tr>
<tr>
<td>E</td>
<td>CEM IV/B, VLH IV/B(V)</td>
</tr>
<tr>
<td>F</td>
<td>CEM III/B+SR</td>
</tr>
<tr>
<td>G</td>
<td>SRPC</td>
</tr>
</tbody>
</table>

For cement and combination types, compositional restrictions and relevant Standards, see Table D3

### Notes
- The classification is B if the cement/combination strength class is 42,5 or higher and C if it is 32,5.
D5.3 Cement and combination types

D5.3.1 Recommendations in Tables D2 and D3
The cements and combinations specifically recommended by this Special Digest for use in aggressive ground are listed as Groups A to G in Tables D2 and D3.

The Groups are defined in Table D3 primarily in terms of resistance to sulfate attack. The designations used are based on those of BS EN 197-1:2000 Cement and BS 8500:2002 for combinations. A suffix ‘+SR’ has been added to the designations where a restriction on some element of the composition is necessary in respect of sulfate resistance.

Cements and combinations of the same composition are treated as being directly equivalent and are always grouped together. Additionally, different types such as CEM II/B-V+SR (a fly ash cement) and CEM III/A+SR (a blastfurnace cement) that show closely similar resistance to sulfate attack are placed in the same Group (in this example, Group D).

While the grouping and nomenclature in Table D3 is different to that of Digest SD1:2003, it should be noted that, in most cases, the requirements of cements and combinations with respect to enhanced sulfate resistance remain unchanged.

In the case of magnesium sulfate, there is some evidence from laboratory tests that certain cements, in particular those containing ground granulated blastfurnace slag (ggbs) or fly ash (pfa), are more susceptible to the conventional form of sulfate attack at very high concentrations of magnesium sulfate than concrete made with sulfate-resisting Portland cement (SRPC). Where cements containing ggbs are used in concrete that contains more than a few percent carbonate, this attack by magnesium sulfate seems to be counteracted.

In contrast, in respect of TSA, concrete containing ggbs cement CEM III/B+SR or ggbs combination CIIIB +SR has a significantly better performance than concrete made with SRPC. As the typical ground temperatures in the UK are conducive to TSA, the cement and combination types for DC-4m concrete have consequently been changed in Table D2 from SRPC to CEM III/B+SR and CIIIB +SR respectively.

No restrictions on the type of cement to resist acid attack are given because the rate of erosion of concrete surfaces by natural acidic waters is affected less by the type of cement than by the quality of the concrete. Consequently, Table D3 does not differentiate between Groups A to G inclusive for DC Classes with a ‘z’ suffix.

D5.3.2 The expert use of special cements
The expert use of special cements, such as supersulfated cement conforming to BS 4248, or calcium aluminate cement conforming to prEN 14647 (until published, refer to BS 915) can produce concretes with very good chemical resistance. Supersulfated cement is not currently produced in the UK, but in high quality concrete it has good sulfate resistance and a good reputation for acid resistance provided particular care is taken in the surface curing.

Current research on the durability of calcium aluminate cement concrete indicates that its high sulfate and acid resistance is due in part to the formation of a resistant surface zone. Close control must be maintained over the mix proportions, temperature, curing conditions and free water/cement ratio, or there will be a risk that conversion could reduce the strength and chemical resistance of the concrete. A minimum cement content of 400 kg/m³ and a total water / cement ratio of not more than 0.40 should be used. Additionally, preventing the surface of the concrete from drying out during the first day of curing will ensure continued hydration and help to maintain the protective surface zone.

Calcium aluminate cements are not covered by BS 8110 or BS 8500, but recent revisions to the Building Regulations Approved Documents do not preclude their use in structural concrete provided long-term properties are adequate for purpose and can be reliably predicted.
### Table D3: Cements and combinations for use in Table D2

<table>
<thead>
<tr>
<th>Type</th>
<th>Designation</th>
<th>Standard</th>
<th>Grouping w.r.t. sulfate resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>CEM I</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td>Portland silica fume cement</td>
<td>CEM II/A-D</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td>Portland-limestone cement</td>
<td>CEM II/A-L</td>
<td>BS EN 197-1</td>
<td>B or C</td>
</tr>
<tr>
<td></td>
<td>CEM II/A-LL</td>
<td>BS EN 197-1</td>
<td>B or C</td>
</tr>
<tr>
<td>Portland pozzolana cement</td>
<td>CEM II/A-Q</td>
<td>BS EN 197-1</td>
<td></td>
</tr>
<tr>
<td>Portland slag cements</td>
<td>CEM II/A-S</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CEM II/B-S</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td>Portland fly ash cements</td>
<td>CEM II/A-V</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CEM II/B-V</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CEM II/B-V+SR c</td>
<td>BS EN 197-1</td>
<td>D</td>
</tr>
<tr>
<td>Blastfurnace cements</td>
<td>CEM III/A</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CEM III/A+SR e</td>
<td>BS EN 197-1</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>CEM III/B</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>CEM III/B+SR e</td>
<td>BS EN 197-1</td>
<td>F</td>
</tr>
<tr>
<td>Pozzolanic cement</td>
<td>CEM IV/B</td>
<td>BS EN 197-1</td>
<td>A</td>
</tr>
<tr>
<td>Very low heat pozzolanic cement</td>
<td>VLH IV/B(V)</td>
<td>BS EN 14216</td>
<td>E</td>
</tr>
<tr>
<td>Sulfate-resisting Portland cement</td>
<td>SRPC</td>
<td>BS 4027</td>
<td>G</td>
</tr>
<tr>
<td><em>Combinations conforming to BS 8500-2: 2002, Annex A manufactured in the concrete mixer from Portland cement and fly ash, pfa, ggbs or limestone fines:</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 6 % to 20 % of combination of fly ash conforming to BS EN 450 or pfa conforming to BS 3892-1</td>
<td>CIIA-V</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 21 % to 35 % of combination of fly ash conforming to BS EN 450 or pfa conforming to BS 3892-1</td>
<td>CIIB-V</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 25 % to 35 % of combination of fly ash conforming to BS EN 450 or pfa conforming to BS 3892-1</td>
<td>CIIB-V+SR</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>D</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 36 % to 55 % of combination fly ash conforming to BS EN 450 or pfa conforming to BS 3892-1</td>
<td>CIVB-V</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>E</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 6 % to 35 % of combination of ggbs conforming to BS 6699</td>
<td>CII-S</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 36 % to 65 % of combination of ggbs conforming to BS 6699</td>
<td>CIITA</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 36 % to 65 % of combination of ggbs conforming to BS 6699</td>
<td>CIITA+SR e</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>D</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 66 % to 80 % of combination of ggbs conforming to BS 6699</td>
<td>CIIB</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 66 % to 80 % of combination of ggbs conforming to BS 6699</td>
<td>CIIB+SR e</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>F</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 6 % to 20 % of combination of limestone fines conforming to BS 7979</td>
<td>CIIL-A</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>B or C</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 6 % to 10 % of combination of silica fume conforming to BS EN 13263 h</td>
<td>CIIL-A</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>B or C</td>
</tr>
<tr>
<td>CEM I cement conforming to BS EN 197-1 with a mass fraction of 6 % to 20 % of combination of metakaolin conforming to an appropriate Agrément certificate</td>
<td>CIIL-Q</td>
<td>BS 8500-2: 2002, Annex A</td>
<td>A</td>
</tr>
</tbody>
</table>
Table D4: Options available to provide Additional Protective Measures for buried concrete

<table>
<thead>
<tr>
<th>Option Code</th>
<th>Additional Protective Measure (APM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APM1</td>
<td>Enhanced concrete quality (see Section D6.2)</td>
</tr>
<tr>
<td>APM2</td>
<td>Use of controlled permeability formwork (see Section D6.3)</td>
</tr>
<tr>
<td>APM3</td>
<td>Provide surface protection (see Section D6.4)</td>
</tr>
<tr>
<td>APM4</td>
<td>Provide sacrificial layer (see Section D6.5)</td>
</tr>
<tr>
<td>APM5</td>
<td>Address drainage of site (see Section D6.6)</td>
</tr>
</tbody>
</table>

Notes to Table D3

a The classification is B if the cement/completion strength is class 42.5 or higher and C if it is class 32.5.

b Metakaolin only.

c The addition of the abbreviation ‘+SR’ denotes an additional requirement for sulfate resistance, that the fly ash content should be a mass fraction of not less than 25% of the cement or combination. Where it is less than 25%, the grouping with respect to sulfate resistance is ‘A’.

d Cements or combinations with higher levels of slag than permitted in this table may be used for certain specialist applications, but no guidance is provided in this Special Digest or BS 8500.

e The addition of the abbreviation ‘+SR’ denotes an additional requirement for sulfate resistance, that where the alumina content of the slag exceeds 14%, the tricalcium aluminate content of the Portland cement fraction should not exceed 10%. Where this is not the case, the grouping with respect to sulfate resistance is ‘A’.

f CEM IV/A cement with siliceous fly ash should be classified as CEM II-V cement.

g Siliceous fly ash only.

h Until BS EN 13263 is published, the silica fume should conform to an appropriate Agrément certificate.

i These combinations are not currently covered by BS 8500-2: 2002, Annex A. However, silica fume can be used in accordance with Clause 5.2.5 of BS EN 206-1:2000.

j These combinations are not currently covered by BS 8500-2: 2002, Annex A. However, metakaolin conforming to Clause 4.4 of BS 8500-2:2002 may be used in accordance with Clause 5.2.5 of BS EN 206-1:2000. If the k-value concept is used, a k-value with respect to sulfate resistance of 1.0 should be used.
D5.4 Aggregate type
In Digest SD1:2001, it was necessary to divide the aggregates into carbonate ranges. For the reasons given in D5.1, this is no longer necessary and the type of aggregate need no longer be taken into consideration.

D6. Additional protective measures (APM)

D6.1 General
A list of the five currently recommended options for APM are provided in Table D4.

Predecessor BRE Digests have always recommended the use of ‘surface protection’ as an additional protective measure for the highest level of sulfate conditions. However, in Digest SD1:2001, multiple protective measures (designated APM) were introduced to compensate for a lack of field and laboratory data in combating TSA. These APM were frequently applicable in less aggressive AC-3 and AC-4 conditions.

As a result of new research findings (see Section A3) and the revision of guidance on the composition of concrete for given DC Classes (Section D5.1), there is an additional confidence in designed concrete quality. Consequently, it has generally been possible here to reduce the number of APM to be applied by two and still have robust recommendations.

The APM that are recommended for each ACEC Class and Intended Working Life are shown in Table D1. APM are needed when the ground conditions incline to being more highly aggressive and/or a higher Intended Working Life is required. No APM are generally required where the ACEC Class has a suffix ‘s’, indicating Static groundwater conditions, as defined in Section C3.1. An exception is where the hydrostatic head across the concrete is more than five times the section thickness (see Note ‘a’ of Table D1). An APM may also be needed where the concrete section thickness is 140 mm or less (see Note ‘b’ of Table D1).

In the most aggressive conditions, Table D1 recommends the provision of surface protection (APM3). However, there are situations where this is not practical (see Note ‘f’ of Table D1), for example for concrete used in friction piles. In this case some other protective measure needs to be found. In theory, this can be any of the other APM options since each APM is given equal status. However, engineering judgement should be used to choose the most appropriate.

When concrete is surface-protected (APM3 applied), no additional APM are needed to meet any consideration of low section thickness or hydrostatic pressure.

D6.2 Enhanced concrete quality – APM1
This APM provides greater resistance to aggressive chemical conditions by increasing the specified DC Class by one step, to a higher DC Class carrying the same suffix, if present.

Examples based on Table D1 are:
- A design Chemical Class of DC-3 is initially identified together with a requirement for ‘one APM of choice’. Increasing the concrete quality to DC-4 can satisfy this.
- A design Chemical Class of DC-2z is initially identified, together with a section thickness of less than 140 mm. The ‘Note b’ requirement for ‘a one-step higher DC Class or an additional APM’ can be satisfied by increasing the concrete quality to DC-3z.

Option APM1 is not available when the initially identified Classes from Table D1 are DC-4, DC-4z and DC-4m.

D6.3 Use of controlled permeability formwork – APM2
The use of controlled permeability formwork (CPF) enhances the in-situ quality of the concrete in the cover zone relative to that achieved with conventional methods. It has been shown to be able to produce a reduction in the water/cement ratio of concrete close to the interface with the formwork, extending to a depth of 10-15 mm into the concrete. Concomitant modifications of porosity have also been reported which, combined with the reduction in water/cement ratio, produce a very dense, low-porosity surface zone in concrete cast against CPF. Tests on this surface zone have indicated improvements in many of its properties compared with concrete cast against conventional formwork. These include improvements to durability-related properties such as permeability to water and oxygen, carbonation, freeze-thaw resistance and chloride ingress. Although no comparative testing of sulfate resistance has been reported, the above improvements in durability properties strongly indicate that sulfate resistance will be likewise enhanced.
The use of CPF should follow the manufacturer’s recommendations.

D6.4 Surface protection – APM 3
Two types of surface protection are considered here: coatings and water-resisting barriers. Appropriately chosen and applied, initially these should completely protect concrete from aggressive chemical action and it might be thought that the quality of the concrete is not relevant. It is essential, however, that a high quality concrete is employed to cover the situation where the surface protection is damaged and it is a number of years before this is noticed and corrected.

D6.4.1 Coatings
The main requirements of coatings are that they should:
- provide an impermeable barrier;
- be resistant to sulfates and other deleterious chemicals;
- have a neutral effect on the concrete substrate;
- be resistant to mechanical damage;
- be easy to apply;
- have long term durability;
- be cost effective.

In practice, the choice of coating will take account of the condition and accessibility of the surface and previous practical experience. Coatings have changed over the years, with tar and cut-back bitumens being less popular, so long-term field data on currently used materials are limited. Common current choices are rubberised bitumen emulsions. These should give good protection if well applied. Additionally, purpose-designed polymeric-based systems, for example epoxy resins, are now available. These coating systems can give exceptional performance, albeit at a higher initial cost.

The risk of damage to coatings during backfill operations should be considered. Coatings must be applied in accordance with the manufacturer’s instructions, and the workmanship must be of a high standard to maintain integrity.

D6.4.2 Water-resisting barriers
The functional and practical requirements for water-resisting barriers are similar to those of coatings (see D6.4.1). Sheet materials are commonly used, including plastic and bituminous membranes. The former is commonly installed before placing the concrete: a 300 micron (1200 gauge) polythene membrane is commonly used to line excavations for trenchfill foundations in aggressive ground, or to cover a site prior to casting a raft foundation. Other types of membrane may be applied to the surface of the concrete after curing. The effectiveness of integral waterproofing agents in preventing sulfate attack is not established.

D6.5 Sacrificial layer – APM4
For this APM, the thickness of concrete is increased to absorb all the aggressive chemicals in a sacrificial outer layer. The quality of this additional concrete should be equal to or higher than that of the inner concrete. Using this measure is not appropriate where the surface of the concrete must remain sound to prevent loss of frictional resistance or settlement, for example for skin friction piles.

The life of a structure and the rate of penetration of chemicals into the concrete are the key issues that determine the required thickness of a sacrificial layer, but there is little guidance data. Field investigation of severe TSA on motorway bridge sub-structures, built with Portland cement concrete containing carbonate aggregate and buried in reworked pyritic clay, showed attack to a depth of up to 50 mm in about 30 years[^2]. The choice of Portland cement in this case was based upon the sulfate content of the pyritic clay during the original site investigation. However, subsequent backfilling with the clay appeared to have led to an increase in the sulfate content to a level for which the choice of Portland cement would have been inappropriate. (See Section C5.1.2 for guidance on determination of potential sulfates due to oxidation of sulfides).

In using this example of the rate of penetration of TSA as a basis for recommending a suitable thickness for a sacrificial layer of concrete, it must be borne in mind that Portland cement was used, rather than one of the sulfate-resisting cements listed in Table D3. The recommendations here should lead both to a more accurate assessment of aggressive ground conditions and to an appropriate specification for the concrete to be used. It seems reasonable, therefore, an additional surface protective layer of sacrificial concrete 50 mm thick would be adequate for, say, 120 years service life of a reinforced concrete structure.

This extra thickness of concrete should be treated as additional to the specified nominal cover, including situations where concrete is cast directly against the earth and the specified nominal cover is greater or equal to 75 mm in accordance with Clause 3.3.1.4 of
BS 8110: Part 1: 1985. The additional thickness should also be ignored for the purpose of crack width calculation.

If APM4 is to be adopted and blinding concrete is to be used as part of the APM, the blinding concrete should be of the same quality as the foundation construction.

In general, it should be realised that some attack of this sacrificial concrete can be expected. Caution should be exercised in the use of this APM if such attack could affect the structural integrity, for example by introduction of expansive forces or the reduction of frictional forces.

D6.6 Addressing site drainage – APM5
The concept of this measure is to consider routes by which aggressive groundwater can reach below-ground concrete and, where necessary, to modify the site drainage to minimise contact between the groundwater and concrete.

For all sites, the engineer should consider the implication of the proposed development on the ground and surface water regimes. If ‘addressing site drainage’ is being utilised as an APM, the engineer will need to carry out a detailed assessment of water movements before (see Section C3) and after construction. As indicated below, there are various options available to reduce the risk of aggressive groundwater coming into contact with buried concrete including, ‘deemed to satisfy’, redesigning the structure to avoid the drainage problems, and the construction of cut-off barriers and cut-off drains. Care is needed during construction to avoid temporary or permanent situations which increase risks. Drains should be inspected and maintained to avoid leakage close to buried concrete.

There will generally be three groundwater/concrete environments to be considered in respect of addressing drainage as an APM:

- After construction, the concrete will be surrounded by relatively impermeable ground, such as undisturbed clay strata, through which there is little or no movement of groundwater. In this situation, the APM relating to site drainage is deemed to be already satisfied for concrete, provided it is not subject to a hydrostatic gradient from groundwater of greater than five times the thickness of the concrete. In particular, a consideration of groundwater pressures will be needed for structures such as basements and retaining walls that have one side exposed to air.

- It is initially intended that naturally impermeable ground surrounding the concrete be cut through, for example by excavation for construction access or trenches for service pipes, allowing access to groundwater from more permeable ground and/or to surface water. The recommended APM can sometimes be achieved by redesigning the works so that the concrete remains surrounded by impermeable ground that forms a barrier to movement of aggressive groundwater. For example, using a piled foundation or trenchfill foundation for a structure, rather than a spread footing constructed in an open excavation. If breaching the naturally impermeable ground around concrete is unavoidable, the APM can often be achieved by resealing the possible routes by which groundwater can reach the concrete. Alternatively, it can be achieved by designing site drainage that will conduct the groundwater in trenches and excavations away from the concrete, rather than towards it. As noted in Section C3, it is particularly important in aggressive ground conditions to avoid the situation where a backfilled excavation acts as a sump, ponding water against the structure. This would be particularly aggressive to concrete if the backfill contains sulfate or sulfide-bearing material, for example pyritic clay.

- The concrete will be surrounded by relatively permeable ground; here, the recommended APM can be achieved by installing site drainage to remove any aggressive groundwater from the vicinity of the concrete and conduct it safely away. The local authority and/or the Environment Agency may need to be consulted to ensure that any change in the drainage does not adversely affect surrounding land and groundwater.

Particular care is needed with site drainage if there is a source of flowing groundwater on the site (see Section C3.3). Large housing developments and civil engineering works, particularly road and bridge construction, usually disrupt the natural drainage. Usual procedure is to accommodate identified water-courses in the new site layout, or for them to be efficiently diverted. However, in permeable ground, particularly on or adjacent to slopes, many minor water channels may exist that could be a source of aggressive highly mobile water, albeit intermittently.
Construction works themselves, particularly trenches for the access of services to buildings, may create further pathways for flows of groundwater.

D7. Intended Working Life
In Digest, SD1:2001, recommendations for the durability of concrete in the ground used the concept of Structural Performance Level (SPL) to take into account factors such as the consequence of serious chemical attack, the ease of repair and the required working life of the structure. The use of the term SPL has been discontinued and replaced in Table D1 by ‘Intended Working Life’. This alternative performance factor brings this Digest in line with BS EN 206-1: 2000 and provides for the generality of building structures to have working lives of ‘at least 50 years’ and civil engineering structures ‘at least 100 years’. Since the concept does not inherently take into account the consequence of chemical attack, it is extended by Notes ‘d’ and ‘e’ in Table D1:

- to place the foundations of low-rise domestic housing in the ‘at least 50 years’ category, whatever the actual required working life. This is because the structural effects of chemical attack will generally be detected as a serviceability problem long before any instability is threatened and also will be relatively easily repaired by current underpinning techniques. Placing concrete for low-rise domestic housing in a higher performance class would result in unjustified expense in this major building sector.
- to place any concrete elements, which, if they failed, would result in serious consequences, in the ‘at least 100 years’ category, whatever the actual required working life. Examples of such serious consequences could include: major expense owing to difficulty of repair; instability of a structure; or spillage of hazardous materials.

D8. Contract documentation
Clients, designers and specifiers should ensure that the recommendations of this Special Digest are included in contract documents. The preferred approach is for the specifier to provide sufficient information to allow a contractor and concrete supplier to offer ‘a package’ of proposals to comply with the recommendations, as it could provide the basis for alternative specifications being offered that may reduce construction costs. Such information should include as a minimum for each structure:

- Intended Working Life;
- DS Class of the ground;
- Aggressive Chemical Environment for Concrete (ACEC) Class of the ground;
- Concrete strength class;
- Inclusion in the construction design of any details which could be regarded as Additional Protective Measures, for example drainage, permanent surface protection to concrete;
- Other concrete restrictions;
- Other site constraints.

Some contracts may alternatively opt for full prescription of the concrete requirements and APM. In this case the contact documentation should contain:

- DS Class of the ground;
- ACEC classification of the ground;
- Design Chemical Class (DC Class) of concrete;
- Any restriction on cement or combination group;
- Required concrete strength class;
- Number and (optionally) type of Additional Protective Measures (APM) required;
- Other concrete restrictions;
- Other site constraints.

The project specification should clearly state whether any APM are needed that are not shown on the Contract drawings and whether any particular types are required or preferred.

The contract between the contractor and the concrete producer should always include:

- DC Class of concrete;
- Maximum aggregate size.
- Consistence.

The contract may include:

- Strength class of concrete;
- Any further restrictions on cement or combination group;
- Any other requirements.
References – Part D


British Standards Institution
BS 3892: Pulverized-fuel ash
BS 4027: 1996 Specification for sulfate-resisting Portland cement
BS 4248: 1974 Specification for supersulfated cement
BS 6699: 1992 Specification for ground granulated blastfurnace slag for use with Portland cement
BS 7979: 2001 Specification for limestone fines for use with Portland cement
BS 8110: Structural use of concrete
  Part 1: 1985 Code of practice for design and construction
BS 8500: 2002 Concrete – Complementary British Standard to BS EN 206-1
BS EN 197-1: 2000 Cement
  Part 1: Composition, specification and conformity criteria for common cements
BS EN 206-1: 2000 Concrete
  Part 1: Specification, performance, production and conformity
BS EN 450: 1995 Fly ash for concrete – Definitions, requirements and quality control
BS EN 13263 (to be published) Silica fume for concrete
BS EN 14216: 2004 Cement – Composition, specifications and conformity criteria for very low heat special cements
prEN 14647: 2004 Calcium aluminate cement: Composition, specifications and conformity criteria